Positively Scintillating Neutral

Ultrasensitive detectors reveal rare particle interactions that could help scientists improve global nuclear security and advance fundamental physics research.

SINCE the 1930s, when Austrian-born physicist Wolfgang Pauli first theorized the existence of the neutrino, this tiny, nearly massless particle with no charge has made mighty contributions to scientific exploration. Researchers first thought the neutrino would be undetectable because it seldom interacts with matter and is not affected by the electromagnetic force. But its existence was proven 25 years later when its antiparticle, the antineutrino, was detected as a by-product of the fission process occurring in a nuclear reactor. Ongoing studies continue to reveal the mysterious properties and behaviors of neutrinos and other neutral particles.

For nearly a decade, the Laboratory has been a leader in demonstrating the utility and robustness of detectors that can identify the rare interactions between neutral particles. Working with research and academic institutions worldwide, Livermore scientists are applying computational resources and technological advances to improve the measurement fidelity and sensitivity of these devices.

In a nonproliferation project completed in 2008, researchers from Lawrence Livermore and Sandia national laboratories deployed a prototype detector at a nuclear reactor and demonstrated that the detector precisely tracked the flux of antineutrinos emitted by the reactor core. “At Livermore, we’re also involved in two basic science experiments: one to better understand the oscillation properties of neutrinos and the other to directly measure, for the first time, interactions of dark-matter particles in a detector on Earth,” says Adam Bernstein, who leads Livermore’s advanced detectors group. “Rare neutral particle detection underlies nuclear security and fundamental nuclear science.”

A detector’s application influences decisions regarding its construction, cost, and operability. For example, a system built to monitor nuclear reactors for international safeguards must have a cost-effective design that is easy to replicate, has low maintenance requirements, and can be readily used in various locations. Detectors for specialized physics experiments, on the other hand, can be more elaborate and may be designed for one-time operation.

For users to have confidence in the acquired data, both types of systems must efficiently distinguish a signal of interest from background noise. Detectors also must be sensitive enough to measure particle interactions with kilo- to megaelectronvolt energies, in particular those from electromagnetically neutral particles such as gamma rays and neutrons, dark-matter particles, and antineutrinos.

A New Regime in Reactor Monitoring

Inside a nuclear reactor, antineutrinos are produced through the fission of plutonium and uranium isotopes within the core. (See *S&TR*, January/February 2006, pp. 21–23; July/August 2008, pp. 23–25.) During the fuel cycle of a typical reactor, the number of antineutrinos emitted from the core decreases as plutonium

Livermore physicists Nathaniel Bowden (left) and Timothy Classen calibrate a scintillator-based antineutrino detector before deployment. These massive systems can weigh up to 20 tons and measure more than 3 meters per side. The background image, taken by the Hubble Space Telescope, shows the galaxy cluster MACS J1206. Clusters such as these have enormous mass, much of which is theorized to be dark matter. The Laboratory’s expertise in neutral particle detection is also being used to directly characterize these particles. (Background image courtesy of National Aeronautics and Space Administration, European Space Agency, and Space Telescope Science Institute.)

Particles Brighten Scientific Prospects

"I have done a terrible thing, I have postulated a particle that cannot be detected."

—Wolfgang Pauli

content builds. By using this flux rate and the known thermal power of the reactor, operators can track antineutrino emissions throughout a core's one- to two-year lifespan and identify abnormal shifts.

Scintillator-based detectors, which measure inverse beta-decay events, are the most effective technology for monitoring the flux rate from a reactor. When an antineutrino collides with a proton in the scintillation liquid, the interaction produces a positron and a neutron that induce a measurable signature—two bright flashes of light occurring almost simultaneously. (See the movie at str.llnl.gov/Dec12/images/antineutrino.mov.)

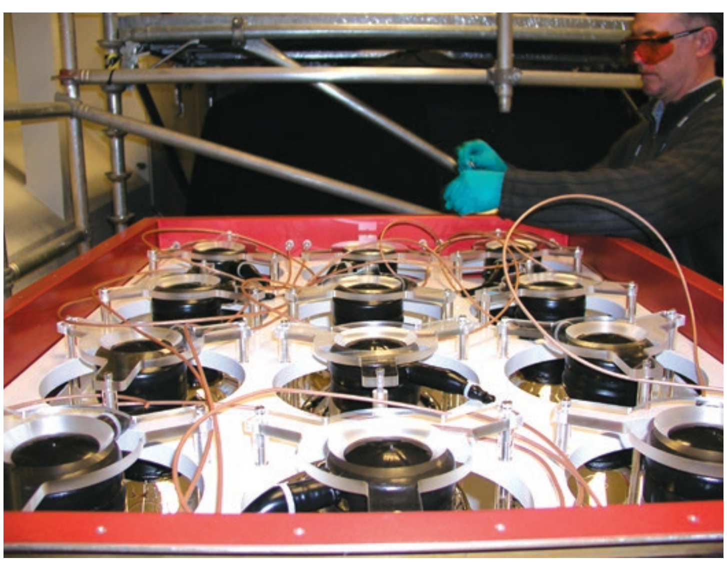
The Livermore–Sandia demonstration in 2008 showed that scintillator detectors operating 10 meters underground and 25 meters from a reactor core can detect an anomalous flux in antineutrino emissions, which in turn reveals changes in fissile content. However, such detectors weigh up to 20 tons, with each side measuring 3 meters or more—a size that reduces the number of possible deployment locations at nuclear reactor sites.

In 2010, Livermore researchers began testing a water-based detector that is still rather large—it fits inside a standard cargo container—but offers several advantages over scintillator-based systems. (See *S&TR*, September 2010, pp. 20–22.) "Water is likely the only material that can be scaled in a cost-effective and environmentally safe way to the hundreds of kiloton detector sizes required for remote monitoring," says Bernstein. "The only other viable alternative, liquid scintillator, is far more expensive to procure and maintain, increases handling risks to workers, and is more damaging to the environment."

In addition, water is inherently more resistant to the background signals produced by cosmic rays. As a result, a water-based detector might operate aboveground without heavy shielding, thereby greatly simplifying the deployment process at nuclear reactors. Unfortunately, tests of the Livermore prototype revealed only marginal sensitivity for aboveground operations because of residual background signals.

Bernstein notes that the basic detection concept remains viable, and his team is working on a Laboratory Directed Research and Development project to explore a revamped water-based detector. Because antineutrino flux drops as it travels away from a reactor core, a detector designed for long-distance monitoring must be large enough to provide the required probability for particle interaction with atoms inside. By building a detector with cheaper materials, the team can increase the detector's size and thus extend the range of detection.

The team has completed a conceptual design for a 1-kiloton water-based detector to identify an antineutrino signal several kilometers from a reactor. If the new system is successful, it will be the first water-based detector used to monitor reactor antineutrinos. It would also allow researchers to gain insight into the characteristics of even larger systems for true remote operations in support of the nation's nonproliferation efforts.



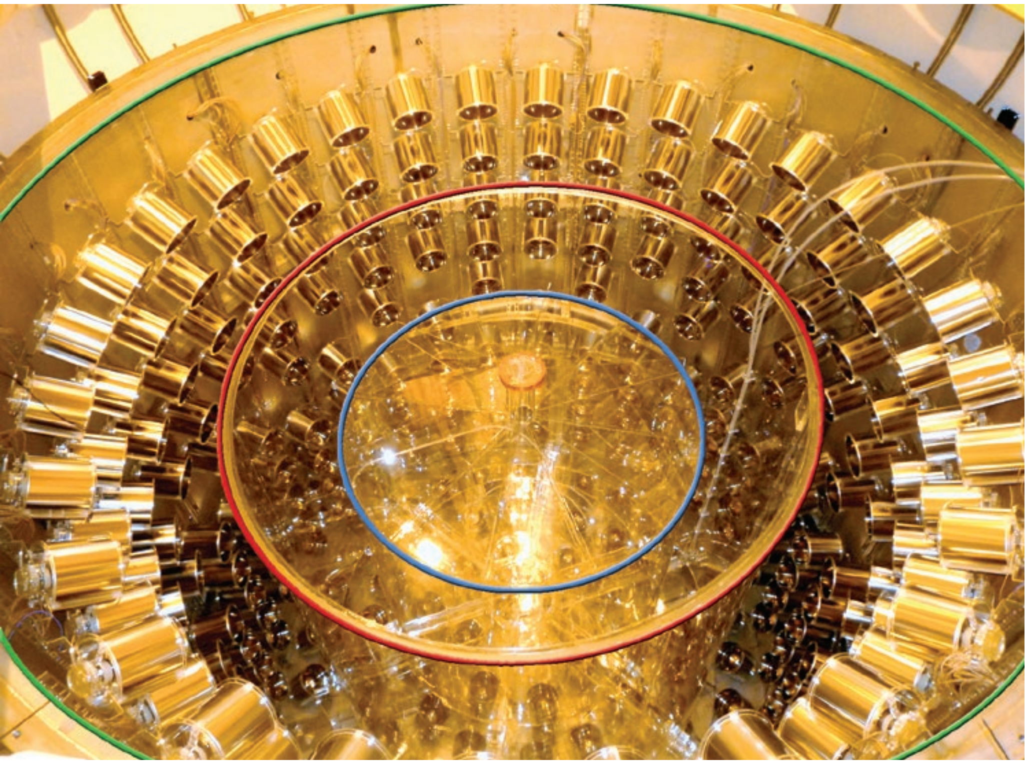
The water-based antineutrino detector developed at Livermore contains a mixture of water and gadolinium. Physicist Steve Dazeley fits the 1-ton device with an array of 12 photomultiplier tubes, each about 25 centimeters in diameter, to record the signal of interest.

A "Flavor"-full Mixture

Much like ice cream comes in three primary flavors—vanilla, strawberry, and chocolate—neutrinos have three flavor states: electron, muon, and tau. Scientists theorize that a neutrino can oscillate, or transform, from one flavor to another as it travels from its source. (See *S&TR*, April 2003, pp. 13–19.) Quantum mechanics dictates, however, that oscillation can occur only if neutrinos have mass, even if it is only a tiny amount. Experiments since the mid-1990s have shown that oscillation is possible, indicating that neutrinos do have mass. In fact, oscillation would account for the difference between the number of predicted and detected electron neutrinos emitted by the Sun.

Oscillation parameters, or mixing angles, describe the probability that one type of neutrino will transform into another over a given distance. Researchers have measured two of the three mixing angles. The third, a fixed parameter called theta-13, is considerably smaller than the other two, making it more difficult to detect.

An experiment at the Chooz nuclear power plant in France helped confirm the amount of oscillation between the different neutrino flavors and set lower and upper limits for theta-13. Called Double Chooz, this experiment used a 10-ton



The core of the main detector for the Double Chooz experiment in France contains four concentric cylindrical tanks. The innermost 8-millimeter-diameter tank (blue) is filled with the gadolinium-doped target liquid, which is surrounded by another type of liquid scintillator (red) that captures gamma rays emitted by the target. A buffer layer (green) filled with mineral oil shields the target from background signals and radioactivity generated by the 390 photomultiplier tubes attached to the buffer tank's inner wall. (Photograph courtesy of CEA-Saclay/IFRU-SIS.)

gadolinium-doped scintillation detector to record the signals of antineutrinos emitted by the reactors, which provide a pure source of electron antineutrinos.

For the Double Chooz project, Livermore physicists developed simulations to predict the reactor output. "At any given point, the antineutrino could be in one of the three flavor states," says Greg Keefer, a physicist in the Laboratory's Physical and Life Sciences Directorate. "To have a baseline, we had to predict how many electron antineutrinos would be emitted."

Working with European collaborators, the Livermore team modeled the Chooz reactors using two neutron-transport codes, MURE and DRAGON. MURE is a three-dimensional Monte Carlo–based code that tracks individual particle motion in a reactor, from the moment each neutron appears through fission, until it is ultimately absorbed. DRAGON, a two-dimensional lattice code, solves differential equations to provide an overall average for key parameters.

"We use these complementary models to predict the number of fissions per unit time for each fissile isotope over the running period of the reactor cores," says Keefer. "We can then assess a systematic error on the predicted number of fissions and fold this number into another code that gives us the number of neutrinos per fission of a specific isotope. The results provide us with a predicted antineutrino rate as a function of time and an estimated error on the predicted rate."

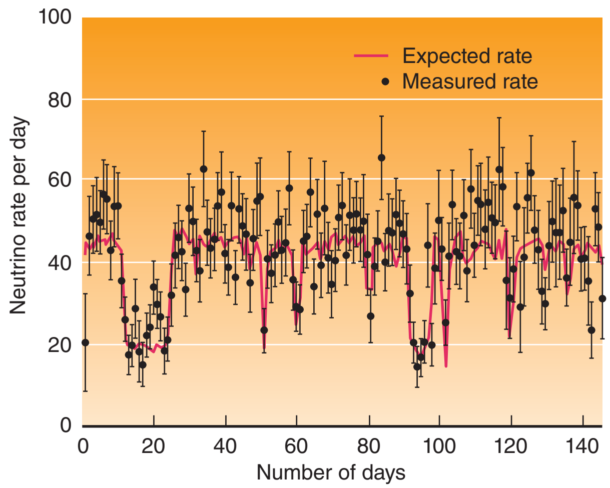
The Laboratory's experience in modeling reactor cores for nonproliferation efforts has been an asset for the Double Chooz experiment. "We have created high-fidelity simulations to accurately predict reactor output," says Keefer. "We were the first to bring nuclear engineers onboard to help establish input parameters that are more faithful to how a reactor operates." Simulation results compared well with established benchmark data from destructive assays of fuel rods at the Takahama reactor in Japan. "A major part of our effort was validating the benchmark data and improving our understanding of diagnostic and systematic errors to obtain the precise measurements."

When researchers compared the number of simulated antineutrinos with the amount detected in the Double Chooz experiment, they discovered a deficit in the number detected. Bernstein notes that this finding is consistent with some of the electron antineutrinos emitted by the reactor having oscillated into other flavors. "Double Chooz is a so-called disappearance experiment," he says, "and indeed the experiment found that nearly 10 percent of the electron antineutrinos had disappeared, compared with the number that would have been expected if oscillations were not occurring."

The collaboration was the first reactor experiment to identify a deficiency consistent with a nonzero final mixing angle for theta-13. Later experiments have since confirmed these results, indicating that theta-13 is both nonzero and has a magnitude close to previous upper limits.

Bringing Dark Particles into the Light

The putative dark-matter particle is much like the neutrino in at least one respect: Both were theorized to exist based on indirect evidence before they were ever detected. Dark matter is postulated



The observed rate of antineutrino events in the Double Chooz experiment compared well with the predicted rate generated by the DRAGON and MURE neutron-transport codes using thermal power measurements as inputs. The two drops in the rate indicate when the reactor was off or operating at reduced thermal power. The predicted event rate was continuously updated to account for reactor downtime.

to make up about 84 percent of the universe, but it does not emit or reflect electromagnetic radiation. Its composition is therefore unknown.

Astronomical observations indicate that dark matter permeates much (or all) of the known universe. The gravitational influence of this matter alters the structure of visible galaxies and other large-scale astronomical objects. Many theoretical and empirical studies point to a candidate dark-matter particle, known as the weakly interacting massive particle (WIMP).

"Dark-matter particles are expected to be heavy, weighing perhaps 10 to 1,000 times the mass of a proton, but they have no electric charge," says Livermore physicist Peter Sorensen. As a result, they seldom interact with other particles, making them extremely difficult to observe directly. A detector that rigorously suppresses background signals from other particles, such as neutrons that mimic dark-matter signals, might record one true event in many millions.

The Large Underground Xenon (LUX) detector is designed to suppress these background signals so that dark-matter particles can be characterized. "LUX is a dual-phase time-projection chamber for detecting the nuclear recoil signal produced when a dark-matter particle collides with an atom of liquid xenon," says Sorenson, whose involvement with LUX predates his time at the Laboratory.

The initial collision of a dark-matter particle with a xenon atom creates a first flash of scintillation photons (S1) and also produces electrons. While the particle recoils off the atom and continues to travel in space, the electrons are tracked by the detector. An applied electric field causes the electrons to drift up the chamber through the cryogenically cooled xenon into a gas above the liquid. The electric field then accelerates the electrons, and they collide with other atoms in the gas. This collision produces many more photons and creates a second, larger flash of light (S2).

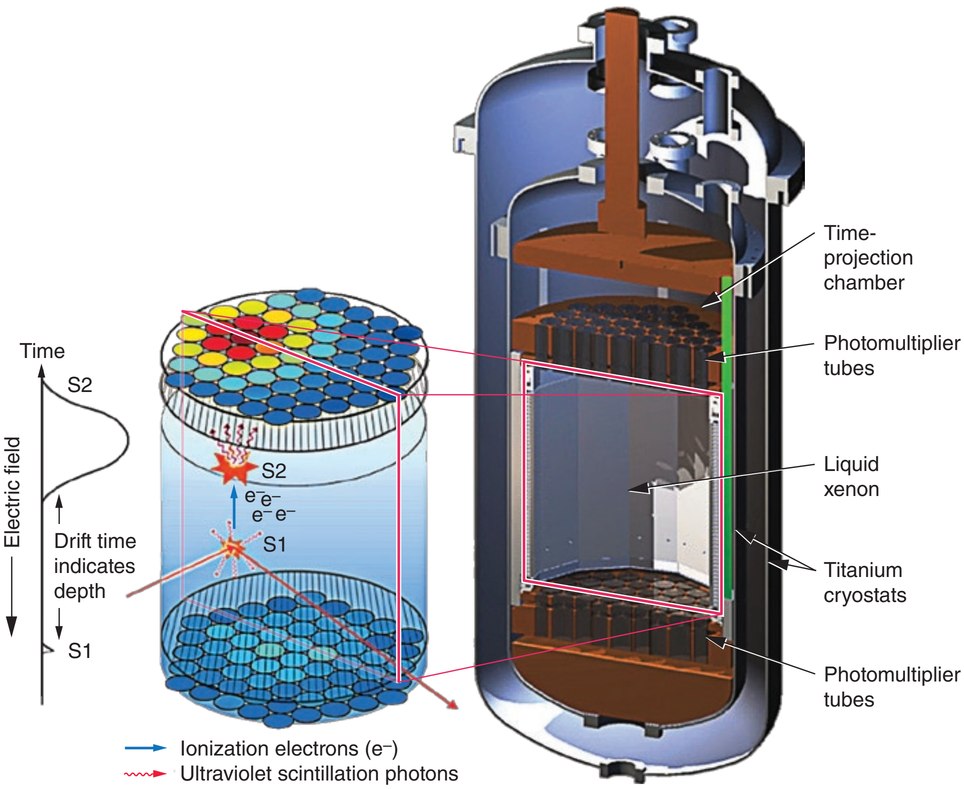
"The S1 flash occurs within about 100 nanoseconds," says Sorensen. "The S2 flash is a factor of 10 more spread out, occurring over microseconds." Photomultiplier tubes detect and measure the amplified light. The intensity of the S1 light and the S2 charge and the time between the two flashes allow researchers to locate the particle interaction. Says Sorensen, "The ratio of S2 to S1 also indicates the incident particle type, whether it's a boring background gamma particle or a neutral particle such as dark matter."

Using xenon instead of lighter elements such as hydrogen or oxygen increases the number of target nucleons with which the "timid" WIMPs can interact. Xenon is also very dense, so LUX is more compact than gas detectors or those that use other less dense materials. As a result, the nuclear recoil event can be precisely localized within a small section of the device. Sorenson says, "We can reconstruct in three dimensions the position of the particle interaction to within a few millimeters, which helps us determine if the interaction was from dark matter or some other known particle physics process, such as a neutron recoil."

LUX's location and construction also protect the detector from background radiation. The detector is deployed 1.5 kilometers underground in the Sanford mine in South Dakota. The overlying rock—called overburden—is the first and best line of defense. "Aboveground, we are bombarded by extremely high-energy muons emitted by cosmic rays," says Sorensen. "On average, one muon passes through an object the size of a human hand every second. Fortunately, rock does a great job of attenuating the muon signal, and these background signals drop exponentially with depth. Underground, one muon might pass through a LUX-size detector less than once per day."

In addition, a seamless "skin" of xenon surrounds and shields the central xenon core, and the device is immersed in a water bath to further stave off neutron signals. With this design, the interactions occurring in the core are most likely to come from dark matter, if it exists.

One of a dozen dark-matter experiments worldwide, LUX was tested aboveground prior to its installation in the mine, where it is being commissioned. Once the system is online, it will operate continuously for 300 days, after which in-depth statistical analysis will be completed to determine whether a dark-matter interaction has occurred. "By effectively suppressing backgrounds to the point where ordinary neutron and gamma-ray interactions are extremely unlikely to cause a recoil, we will be able to establish with high



Inside the Large Underground Xenon (LUX) detector, putative dark-matter particles interact with xenon atoms, creating photons and electrons. LUX immediately records the photons produced in a flash of light called S1. The electrons are extracted into a gas and accelerated, producing an amplified, secondary photon signal (S2). The ratio of S2 to S1 and the time between the two flashes indicate the incident particle type.

confidence that the interaction did not result from a more common physics process," says Bernstein. "Measuring a signal under these circumstances allows us to infer the existence of a new interaction mechanism, consistent with the WIMP hypothesis."

The Livermore team helped design, construct, and deploy many key subsystems for LUX and will be central to analyzing the data. If the detector provides evidence for the existence of dark matter, the results will spark new areas in physics research. "We don't yet know what dark-matter particles are made of or how they interact with ordinary matter," says Bernstein. "It could be a whole new particle zoo. Dark matter may consist of a completely new type of particle, one that we would then have to study and characterize."

A Less Obvious Event

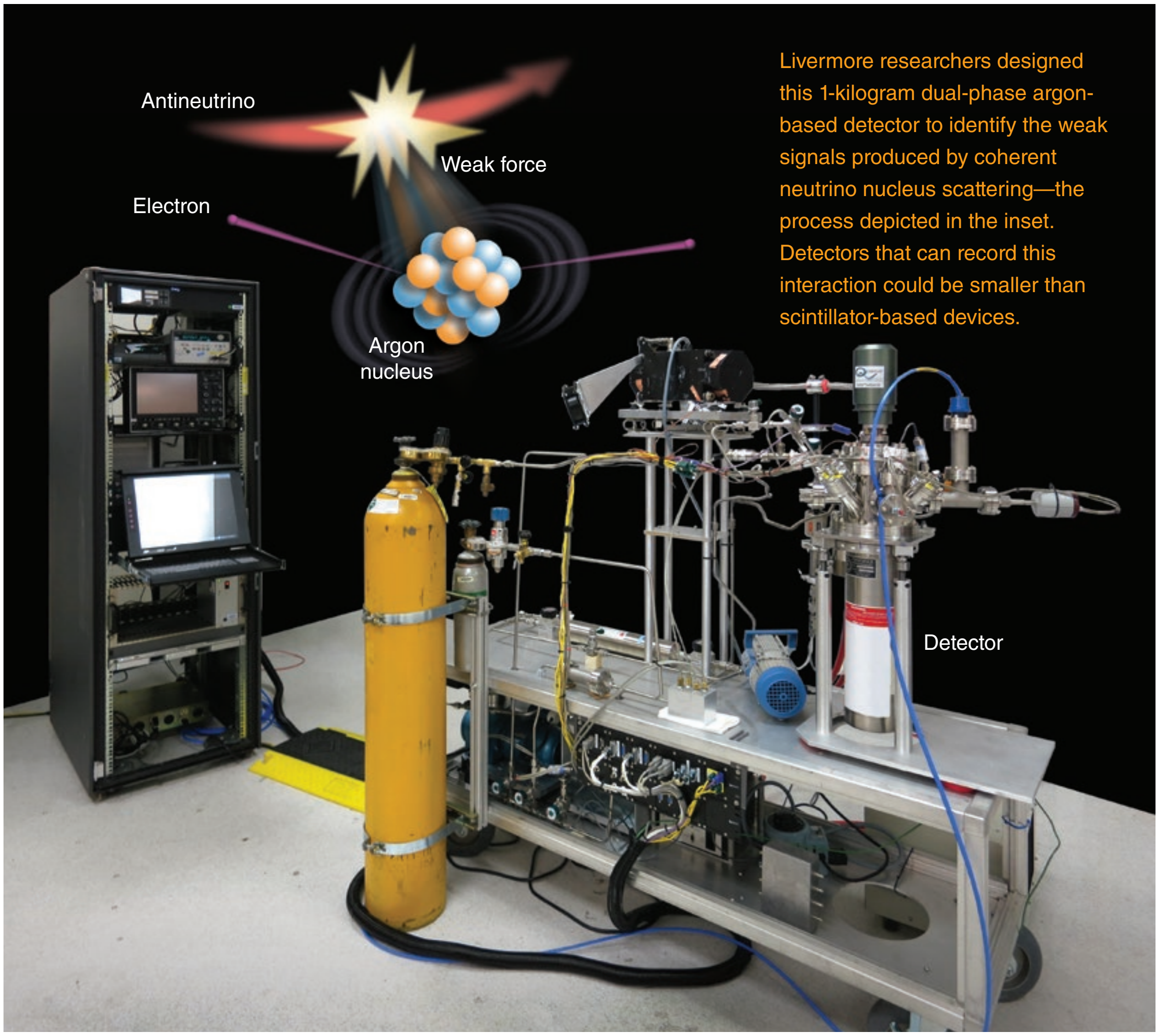
The LUX design is also being used to develop a new class of antineutrino detectors for nuclear security applications. Today's devices rely on inverse beta decay to monitor a reactor's fissile content, but this process is not the most frequent type of antineutrino interaction. More common, but also far more difficult to detect, is coherent neutrino nucleus scattering, in which a recoiling nucleus collides with its neighboring atoms and "shakes" loose a few electrons. Just as wind rustles the leaves on a tree in unison, through coherent scattering, an antineutrino interacts with an entire nucleus rather than with individual nucleons.

Coherent neutrino nucleus scattering has not been observed experimentally, although its detection rates have been well calculated as part of the Standard Model of particle physics. Technology improvements made over the last decade allow much lower energy recoils to be recorded with higher reliability. Building a device to measure coherent scattering would be a breakthrough in antineutrino detector research. Coherent scattering is hundreds of times more likely to occur than inverse beta decay, so smaller devices could record these events. Bernstein says, "We could potentially build systems that are 10 to 20 kilograms as opposed to the 1,000-kilogram detectors needed for inverse beta-decay events."

Livermore scientists have developed a 1-kilogram dual-phase argon-based detector, whose design is akin to LUX. The compact system is designed to record an electron signal in the liquid argon and an amplified signal in the argon gas blanket above the liquid. (See the movie at str.llnl.gov/Dec12/images/scatter.wmv.) The detector also provides three-dimensional event reconstruction of selected signals while minimizing background noise.

Thus far, the novel detector has measured electromagnetic recoils with the lowest energy ever recorded in dual-phase argon. "Our preliminary results indicate that we have achieved sensitivities down to single ionizations," says Bernstein.

Several important hurdles remain before coherent scatter interactions can be measured. First, the team must estimate the expected number of electrons that would be liberated by an antineutrino during an event. To do so, the team will use a neutron beam to impart the same amount of energy to the nucleus as an antineutrino, thereby establishing sensitivity to the few-electron signal arising from antineutrino interactions. Next, the detector must be reconfigured to better suppress background signals. It will then undergo testing at a nuclear reactor. A successful demonstration would be the first-ever measurement of coherent scattering. "Eventually the device might be optimized to fit in the back of a pickup truck," says Sorensen.



Livermore researchers designed this 1-kilogram dual-phase argon-based detector to identify the weak signals produced by coherent neutrino nucleus scattering—the process depicted in the inset. Detectors that can record this interaction could be smaller than scintillator-based devices.

A mobile device for reactor monitoring could be extremely valuable for improving nuclear safeguards.

Work Sparks Growing Interest

According to Bernstein, neutrino research, particularly in the area of reactor monitoring, has gained momentum in the last decade, and an international conference on applied antineutrino physics has been held nearly every year since 2004. "Russian researchers first demonstrated the concept of antineutrino-based reactor monitoring in the mid-1980s," says Bernstein. "Because of the Cold War, this first-rate work was originally available only in Russian journals and thus unknown to us and many other Western researchers. Our 2002 theoretical paper and 2006 deployment drew wider attention. As a result, the topic is now a focus of many neutrino physics groups and conferences worldwide."

By participating in projects such as LUX and Double Chooz, the Livermore team has demonstrated how fusing basic science research with applied physics can yield benefits to both fields of study. Working with experts at the Laboratory provides external collaborators with the types of resources—from experimental hardware to computational capability to unique nuclear physics analyses—that are available only at a national laboratory. In turn, Livermore physicists have been able to adapt new technology for nonproliferation purposes.

"Investments in basic science have led to improved detector designs for reactor monitoring, and our participation in these efforts has helped further fundamental physics understanding," says Bernstein. "Together, we are solving critical global nuclear security problems and promoting high-quality science."

—*Caryn Meissner*

Key Words: antineutrino detection, coherent neutrino nucleus scattering, Double Chooz, Large Underground Xenon (LUX) detector, neutral particle, neutrino, nonproliferation, nuclear reactor monitoring, nuclear security, particle physics, scintillator, weakly interacting massive particle (WIMP).

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